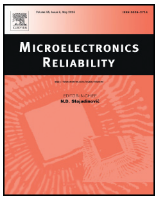
Microelectronics Reliability xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Microelectronics Reliability

journal homepage: www.elsevier.com/locate/microrel



Simulation study on thermo-fatigue failure behavior of solder joints in package-on-package structure

Zhi-Hao Zhang [a], Xi-Shu Wang [a,*], Huai-Hui Ren [a,b], Su Jia [a,c], Hui-Hui Yang [a]

[a] Department of Engineering Mechanics, School of Aerospace Engineering, Tsinghua University, Beijing 100084, PR China
[b] China Longyuan Power Group Corporation Limited, China Goudian, Beijing 100034, PR China
[c] Guangzhou CABR&SC Co.Ltd Architectural Design and Research Institute of Guangdong Province, Guangzhou 510010, PR China

ARTICLE INFO

Article history:
Received 11 April 2017
Received in revised form 18 June 2017
Accepted 18 June 2017
Available online xxxx

Keywords:
Solder joint
Package-on-package
Thermal fatigue
Failure criterion
Simulation analysis

ABSTRACT

In this work, the simulating analysis of PoP structure under the temperature range from 0 °C to 125 °C is carried out using direct thermal-cycle analysis and Coffin-Manson method. The results show that the maximum accumulating inelastic hysteresis energy appears on the solder ball in the bottom fine-pitch ball grid array (FBGA) structure. The thermal-fatigue crack initiates in the two symmetrical corners of solder ball in FBGA structure. The thermal-fatigue damage evolves fast in the outer row corner's balls then slowly propagates into the inner row balls in FBGA structure. By analyzing the failure data of solder balls, a thermal-fatigue failure criterion is defined where the critical failure probability value is about 80%.

1. Introduction

Electric circuits in devices are subjected to various loadings, e.g. mechanical fatigue, thermal fatigue, impact and creep rupture etc. And the failure probabilities caused by the thermal fatigue and mechanical fatigue are about 67% and 13% in their applications, respectively. The ultra-large-scale integrated (ULSI) circuit generally consists of different elements, complex structures and fabrication processes in the micro scale. To assure its failure-free performance and longer service life in the applications, the physical failure models such as the thermal cycling (low cycle fatigue, $N_f < 10^4$) model and mechanical cycling (high cycle fatigue, $N_f = 10^4$–10^7) model have been widely investigated by various failure analysis methods [1–4]. In addition, the increasing requirements for integrated circuit devices with high performance have led to the development of the single-package-stacking multi-die.

Package on package (PoP) is a novel structure consisting of solder joints, top package and bottom package. In recent decade, the technology of logic and memory integration has been matured, which places one package on the top of another to integrate different functions while maintaining compact size. Therefore, it has become the first choice for the industries [4–7]. To obtain a reliable structure, reliability tests should be conducted to assess the performance of PoP. It has been widely used in packaging field for reliability prediction of the PoP structure in different environments such as drop and shock, bend, thermal cycling [8]. Due to the great mismatch in the coefficient of thermal expansion between different elements, thermal cycling fatigue is a common failure mode during its service process. The thermal fatigue behavior of the PoP structure has been widely focused in recent years. For example, Lai and Wang etc. [9–11] investigated the thermal characteristics of a board-level PoP under coupled power and thermal cycling test conditions using the numerical method. The results show that the reliability of the PoP stacking assembly is dominated by the critical FBGA solder joint, and the reliability of the PoP is highly related to the range of temperature excursions and the degree of deviation caused by the coupled power and thermal cycling. Yan and Li [12] studied the effects of different Ag contents of solder on the fatigue lifetime of the Fan-in Package on Package (Fi PoP) by finite element analysis, which indicate that a higher Ag content is available for the enhancement of the thermal reliability. In addition, Lee and Hwang [7] discussed the optimal underfill material for PoP to achieve reliable board level performances. It was found that underfills with lower coefficient of thermal expansion & higher glass transition temperature (Tg) are better than other factors for temperature cycle performance.

Upon the PoP structure, the die attach elements, which usually have enough adhesion strength [13–15], are sandwiched between dies. Compared with the die attach, the weakest element in the PoP structure is the solder joint such as SnPb or SnAgCu solder with low strength' resistance caused by the low melting point. Due to the manufactured defects and the stress/strain mismatch in the interconnections, the crack, accompanied by the primary creep and plastic deformation, is easy to appear at the interface or the surface of solder joint in general. And the

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* Corresponding author.
E-mail address: xshwang@tsinghua.edu.cn (X.-S. Wang).

http://dx.doi.org/10.1016/j.microrel.2017.06.033
0026-2714/© 2017 Published by Elsevier Ltd.

Please cite this article as: Z.-H. Zhang, et al., Simulation study on thermo-fatigue failure behavior of solder joints in package-on-package structure, Microelectronics Reliability (2017), http://dx.doi.org/10.1016/j.microrel.2017.06.033

Nomenclature

α	coefficient of thermal expansion (/°C)
B_1, B_2	constants (/s)
D	damage variable (scalar stiffness degradation)
E	Young's modulus (GPa)
$\overline{E}$	elastic stiffness degradation (GPa)
G	shear modulus of materials (GPa)
L	characteristic length of the element
N	thermal-fatigue cycle
N_{fail}	failure number of solders in PoP structure
N_{total}	total number of solders in PoP structure
Q	activation energy (kJ/mol)
T	temperature (°C)
R	ideal gas constant (J/(mol·K))
$\Delta\varepsilon$	strain range
$\Delta\varepsilon_p$	plastic strain range
$\dot{\varepsilon}$	strain rate
σ	stress amplitude (MPa)
$\Delta\sigma$	stress range (MPa)
σ_m	creep strength of the referring particle free metal matrix (MPa)
σ_{th}	creep strength increment (MPa)
$\vec{\sigma}$	stress tensor after damage of PoP structure (MPa)
$\overrightarrow{\sigma'}$	stress tensor before damage of PoP structure (MPa)
ν	Poisson's ratio
η	thermal failure probability

failure behaviors (especially thermal-fatigue failure behavior) of solder joints exist great difference in different package structures [15,16].

In previous literatures [4,17–22], the interface fracture/fatigue cracking behaviors of solder joints including the surface-mounted technology (SMT) and PoP structure have been studied by the scanning electron microscope (SEM) in-situ experiment and finite element analysis method. The results indicate that the PoP structure has a strictly hierarchical failure behavior under mechanical loadings. In this paper, the thermal-fatigue stress distribution in PoP structure and the thermal-fatigue failure behavior of SnAgCu solder joints are investigated by using direct thermal-cycle analysis and Coffin-Manson method. A thermal-fatigue failure criterion is defined by analyzing the failure data of solder balls.

2. Constitutive equations and damage model of solder materials in PoP structures

2.1. Constitutive equation of solder joint in PoP structure

The classical Wiese' model [23,24] is used in this work as following:

$$\dot{\varepsilon} = \left[B_1\left(\frac{\sigma}{E}\right)^3 + B_2\left(\frac{\sigma}{E}\right)^7\right] \times \exp\left(-\frac{Q}{RT}\right) \tag{1}$$

Table 1
Constants of solder joints in the damage model.

Constants of solder joints (SnAgCu)	c_1	c_2	c_3	c_4
Values	9.88×10^{-5}	1.08	33.30	−1.52

where $E = 56.00–0.088\,T$ (GPa) for SnAgCu solder [23,24], which results in the soften behavior due to the phase coarsening of the intermetallic structure at high temperature T(K). B_1, B_2 are material's constants of 1.7×10^{12}/s, 8.9×10^{24}/s, respectively. σ is the stress amplitude (MPa). Q is the activation energy of about 34.60 kJ/mol [24], which was obtained from creep tests on precipitation strengthened alloys using the creep strength increment $\sigma_{th} = \sigma\text{-}\sigma_m$ [23]. R is the ideal gas constant of 8.31 J/(mol·K). In addition, the empirical constitutive equations of SnPb alloy under cyclic loading at room temperature could be characterized as follows [17,18]:

$$\Delta\sigma = 1.71 \times 10^5 \Delta\varepsilon^{1.47}\ or \Delta\sigma = 1.853 \times 10^5 \Delta\varepsilon_p^{1.44}, (\mathrm{MPa}) \tag{2}$$

where $\Delta\sigma$ and $\Delta\varepsilon$ are the stress and strain range of bulk SnPb solder, respectively. $\Delta\varepsilon_p$ is the plastic strain range. According to the authors' previous reported results [17,18,22], the damage initiation and evolution criteria using the accumulating inelastic hysteresis energy are used for the solder joint in this simulation. As the computational cost to simulate the slow progressive thermal-damage in PoP structure is prohibitively high, the direct cyclic analysis method is applied. This method uses a combination of Fourier series and time integration of the nonlinear material behavior to directly obtain the stabilized response of the structure subjected to periodic loading, so it is suited to the calculations of fatigue behavior for a large and complex structure [21].

2.2. Thermal-fatigue damage model of solder joints in PoP structure

The thermal-fatigue behavior usually occurs in the low-cycle fatigue (LCF) regime of the elements in PoP structure consisting of the solder joints, the top stacked die chip scale package (CSP layers: Die A, Die B and Die C) and the bottom fine-pitch ball grid array (FBGA-Die) package structures. Among these elements, solder joints are focused because it has low strength caused by the low melted point, which can easily induce the failure. Therefore, the thermal-fatigue behavior of solder joints in PoP structure is carried out by using direct cyclic analysis and Coffin-Manson analysis method in this work.

The stress tensor after damage of PoP structure including solder joints can be expressed as following:

$$\vec{\sigma} = (1 - D)\,\overrightarrow{\sigma'} \tag{3}$$

where $\overrightarrow{\sigma'}$ is the stress tensor before damage. D is the damage variable which represents the stiffness degeneration of the element. When $D = 1$, the element is in the state of full damage. The Coffin-Manson method is applied that if the damage initiation criterion is satisfied at

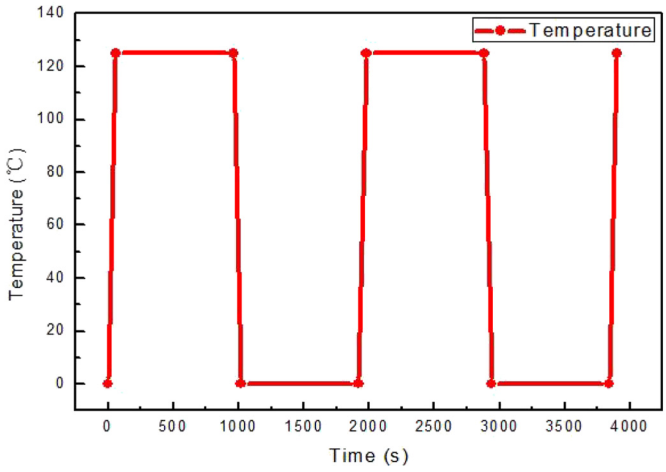

Fig. 1. Thermal-fatigue load curve of PoP structure.

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